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# The Mercury Laser Advances Laser Technology for Power Generation

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## The Mercury Laser Advances Laser Technology for Power Generation

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The National Ignition Facility (NIF) at Lawrence Livermore Laboratory is on target to demonstrate “breakeven” – creating as much fusion-energy output as laser-energy input. NIF will compress a tiny sphere of hydrogen isotopes with 1.8 MJ of laser light in a 20-ns pulse, packing the isotopes so tightly that they fuse together, producing helium nuclei and releasing energy in the form of energetic particles. The achievement of breakeven will culminate an enormous effort by thousands of scientists and engineers, not only at Livermore but around the world, during the past several decades.

But what about the day *after* NIF achieves breakeven? NIF is a world-class engineering research facility, but if laser fusion is ever to generate power for civilian consumption, the laser will have to deliver pulses nearly 100,000 times faster than NIF – a rate of perhaps *10 shots per second* as opposed to NIF’s several shots a day.

The Mercury laser (named after the Roman messenger god) is intended to lead the way to a 10-shots-per-second, electrically-efficient, driver laser for commercial laser fusion. While the Mercury laser will generate only a small fraction of the *peak* power of NIF (1/30,000), Mercury operates at higher *average* power. The design of Mercury takes full advantage of the technology advances manifest in its behemoth cousin (Table 1). One significant difference is that, unlike the flashlamp-pumped NIF, Mercury is pumped by highly efficient laser diodes. Mercury is a prototype laser capable of scaling in aperture and energy to a NIF-like beamline, with greater electrical efficiency, while still running at a repetition rate 100,000 times greater.

As shown in Figure 1, Mercury is seeded by a precision fiber-based laser. This seed pulse is amplified in the preamplifier to an energy of 0.5 J and injected toward the first amplifier. The pulse passes through the first and second amplifiers and is reflected back through both, and then sent back for a 3<sup>rd</sup> and 4<sup>th</sup> pass through the amplifiers to provide optimum energy extraction. After being amplified to its maximum energy, the pulse is directed toward the frequency converter. To date, Mercury has operated for more than 300,000 shots at over 50 J at a repetition rate of 10 shots per second. Ultimately, Mercury’s goal is to generate these pulses with 100 J.

The pumping geometry in Mercury is different than NIF’s, as indicated in Figure 2. By using laser diodes to pump Mercury, we can achieve an order-of-magnitude increase in electrical efficiency in comparison to NIF. Each of Mercury’s two amplifiers is pumped by four 80,000-W laser-diode arrays. The diode light is first angularly redistributed by hollow concentrating optics to a 3x5 cm<sup>2</sup> aperture in which the angular divergence of the beam is made nearly identical in both the x and y axes. The diode light is then guided by a rectangular reflective cavity, which maintains the angular distribution while smoothing the spatial profile.

The amplifiers are face-cooled with high-pressure helium gas, removing approximately 3 W/cm<sup>2</sup> of heat with minimal thermal wavefront distortions. Helium is chosen for two unique properties: its low refractive index and its high thermal conductivity. One advantage of gas cooling is that the technology is scaleable in aperture. Once a system design has been formulated to remove a certain amount of heat per square centimeter, it is possible to scale in aperture, allowing a small-energy (100 J) laser system to operate with the same characteristics as a large-aperture system with 100 times more energy. This heat removal method is applicable not only to the laser gain medium, but also to the frequency conversion system, where the infrared laser emission is converted to green or ultraviolet light.

The design of a complex laser facility is driven by multiple, sometimes conflicting, issues. Here we'll concentrate on three issues involving the selection of gain material, because that selection has the most direct impact on efficiency, cost, and durability. These issues are: quantum defect, upper lasing level lifetime, and emission cross-section. Essentially, these can be translated to the amount of energy (heat) left in the laser gain medium after efficient lasing, the number of diode pump lasers required to effectively provide the gain, and the amount of laser light (fluence) needed to circulate through the laser gain medium to efficiently extract the stored energy.

The quantum defect is important because it determines the amount of waste heat that must be removed from the gain medium. We selected crystalline strontium fluoro-apatite doped with ytterbium (Yb:S-FAP) as the gain medium for Mercury. The ytterbium dopant absorbs diode light near 900 nm and emits near 1047 nm, indicating a quantum defect of 15%. In other words, an absolute minimum of 15% of the pump energy must be removed as waste heat.

The upper-state lifetime is important because it directly affects the number of diode-laser pumps required to achieve a given energy output from the laser. The longer the upper-state lifetime, the longer the diodes have to pump the necessary energy into the population inversion. To achieve a 100-J output with its 15% quantum efficiency, Mercury must pump at least 115 J into its amplifiers' population inversions. Yb:S-FAP has an upper-state lifetime of 1.1 ms, which means it must be pumped with more than 100 kW of diode light. By comparison, if NIF's Nd:phosphate glass were Mercury's gain material, its 360- $\mu$ s lifetime would require three times as many diodes.

Finally, the emission cross-section is important because it determines the gain medium's saturation fluence – the energy fluence needed to extract 63% of the stored energy in a single pulse. Gain materials with a low saturation fluence, like Nd:YAG, whose saturation fluence is 0.62 J/cm<sup>2</sup>, are not well suited for large-aperture, high-energy laser systems. In a large-aperture Nd:YAG system, small amounts of spontaneously emitted energy moving sideways across the aperture can build quickly, depleting the gain available for the main pulse. Nd:phosphate glass has a saturation fluence of 4 J/cm<sup>2</sup>, so large-aperture systems experience manageable losses from amplified spontaneous

emission. With a saturation fluence of  $3 \text{ J/cm}^2$ , Yb:S-FAP is much closer to Nd:glass than Nd:YAG.

The saturation fluence is one example where the lasing efficiency drives an aspect of the laser design. A high saturation fluence (well above that of Nd:glass) can store tremendous amounts of energy per beamline, but requires a high laser fluence (possibly high enough to cause optical damage) in order to extract the energy. In contrast, a low saturation fluence leads to many beamlines. It is likely that a contemporary facility will use a material with a saturation fluence similar to that of Nd:glass, using the tremendous advances in beamline design, fabrication methods, and optical reliability data to fullest advantage. The Mercury laser system uses this developed expertise. Yb:S-FAP was chosen for its similarity to Nd:glass in many aspects (except availability). The combination of long lifetime, moderate drive fluence and aperture scaling, and, especially, the lower energy defect drove the choices from the viewpoint of reducing the cost of diodes required for a 100-J-class laser. If diode costs continue to drop, at some point the necessity of selecting a material based on long lifetime will become less important.

The price of diodes will play a major roll in the commercialization possibilities of laser-driven fusion energy. Diode lasers are currently expensive: In 2001 the diodes for the Mercury laser system were priced at roughly \$1.60 per peak Watt of output power, excluding the cost of the power supply. However, diode lasers are on an aggressive learning curve, shown in Figure 3. With increasing production, diode prices will continue to drop in price from dollars per Watt to pennies per Watt.

A hidden but critical aspect of a laser facility is the control system. Like NIF, Mercury depends on a system of remote alignment and inspection diagnostics. Critical beam optics are continuously monitored. If optical damage occurs during one shot in a high-repetition rate system, it is impossible to shut down the system manually before the next shot causes further damage. Instead, we hand control over to an automatic system. Data from the previous laser shot are compared to the current laser shot. Any significant differences are flagged, allowing the system to be safely stopped before the next shot, preventing potential damage to more than a single optic. Such a data collection and analysis system will be the real brains behind a potential multiple-beamline power-generating system running at a high repetition rate, allowing a safe shutdown and refurbishment of any optical components, as needed.

	Mercury	NIF
Beamlines	1	192
Energy per beamline at $1\omega$ (design)	100 J	18.75 kJ
Fundamental wavelength	1047 nm	1053 nm
Gain medium	Yb:SFAP	Nd:Glass (phosphate)
Gain medium aperture	3 cm x 5 cm	40 cm x 40 cm
Number of slabs	14 (4 pass)	11 (4 pass) + 5 (2 pass)
Slab thickness	0.75 cm	4.2 cm (effective 5 cm)
Total gain medium thickness	42 cm	270 cm
Repetition rate	10 shots per second	4-6 shots per day
Cooling	High velocity helium gas	Radiative and convective
Beam propagation	Image relayed	Image relayed
Pockels cell	KD*P	KDP
Spot size	5 times diffraction limited	5 times diffraction limited
Gain excitation	Diode (900 nm)	Flashlamp
Optical-Optical efficiency	7%	0.7%
Building area	Handball court (800 sq. ft.)	3 football fields (230,000 sq. ft.)

**Table 1. Comparison of the Mercury laser system to the National Ignition Facility**

The goal of the National Ignition Facility is to achieve fusion breakeven. In contrast, the goal of the Mercury laser system is demonstration of a reliable, diode-pumped, solid-state laser system capable of scaling in aperture to the equivalent energy of a single beamline of the 192 beamlines of the National Ignition Facility. Diode pumping reduces the heat deposited into the Mercury laser, while gas cooling allows the residual heat to be efficiently removed.

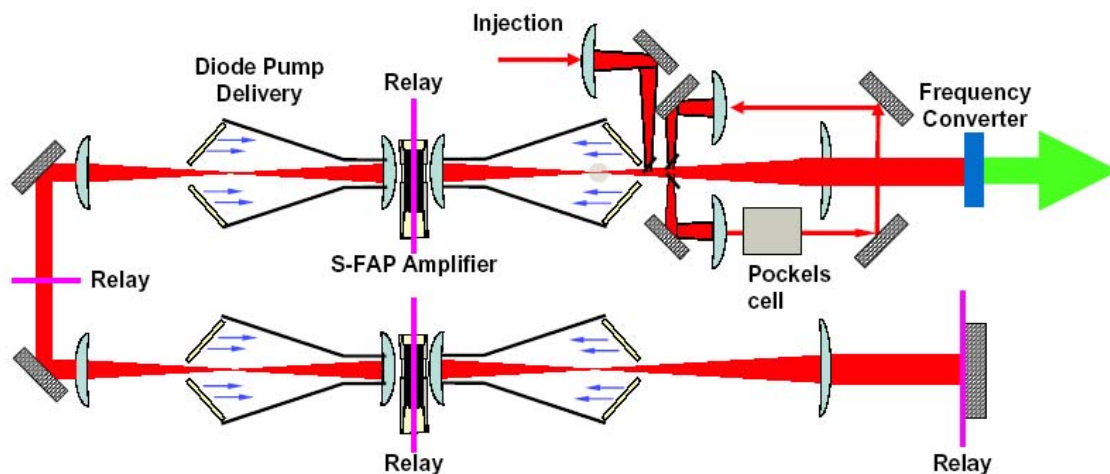


Figure 1. Light from the Front End laser (0.5 J) is injected towards the left into the diode-pumped, helium gas cooled, Mercury laser amplifier. The beam is amplified after passing through each laser head twice. Angular multiplexing allows the beam to bypass the initial injection mirror, and instead traverse through the box of 4 mirrors and the Pockels cell to be re-injected for a series of two more passes, a total of four, one-way gain passes through each amplifier. After the final pass, the beam travels to the frequency converter, where the infrared light is converted to green light, the second harmonic.

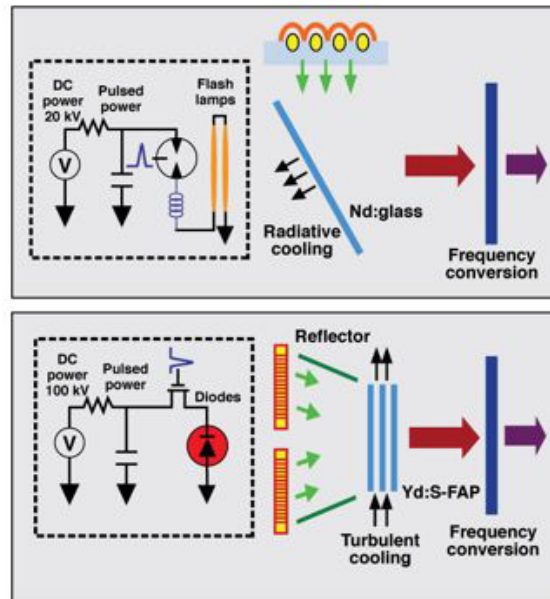
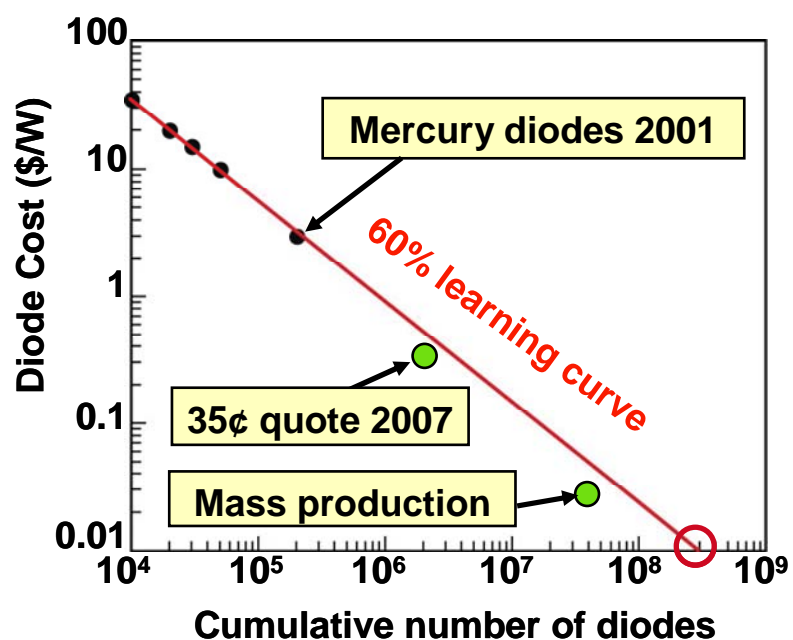


Figure 2. The National Ignition Facility (top) is a flashlamp-pumped laser system, intended to fire up to six shots per day (0.0001 Hz).

To increase the repetition rate by 100,000 (to 10 Hz), the Mercury laser system (bottom) uses active cooling. Diode lasers (as opposed to flashlamps) reduce the thermal loading on the laser gain medium. High-speed helium gas circulates across the amplifier slabs, allowing efficient removal of the residual heat.





**Figure 4.** The cost of gallium arsenide (GaAs) based laser diodes follows a learning curve (dropping of price with a growing market).